Some Comments on Coherent Imagery

This memo will attempt to clarify some concepts of coherent imagery.

Figure 1a shows a coherent imaging system with provision for spatial filtering. This optical configuration is used primarily as an illustration in which each lens performs only one task, for lenses L_1 to L_3 respectively, illumination, formation of the transform and image formation from the transform. A more practical configuration is shown in Figure 1b. In this system, L_4 combines the function of L_1 and L_2. L_4 need be corrected only on axis to form an image of the source at the transform plane while L_2, in conjunction with L_3, must be corrected to image over a field. In addition, while both L_2 and L_5 work at the same F number, determined by the frequency content of the negative, the diameter of L_2 is larger than L_5 by the diameter of the negative. In addition, as will be explained later, the system in Figure 1a is more sensitive to dust, scratches and other localized lens defects.

In coherent imagery there is some order to the light illuminating the negative. This order is lacking in the case of incoherent illumination. The degree of this order determines the degree of coherence. The degree of order present in the illuminating light can be separated into two components, order across the negative called spatial coherence, and order along the optical axis called temporal coherence. These two components are almost independent. Spatial coherence is measured by the degree of collimation or wavefront flatness. Temporal coherence is measured by the range of wavelengths present in the light.

Let us consider the effect of the degree of spatial and temporal coherence upon imagery. First we must distinguish between distance resolution in the image plane and frequency resolution in the transform plane. The resolution element in distance in the image intensity is of the order of the reciprical of the coherent cutoff frequency of the transform plane, and is independent of the degree of spatial coherence. It is the resolution element of the negative, visible in the image that is dependent upon the degree of spatial coherence. On the other hand, the resolution element in frequency in the transform plane for perfect spatial and temporal coherence is of the order of the reciprocal of the negative diameter. If the degree of spatial coherence is such that the image of the source in the transform plane is equal to a frequency resolution element, then the system is spatially coherent. If the degree of temporal coherence is such that when the source image is diffracted by the high frequency content of a negative to the cutoff frequency of the transform plane, the diameter of the source

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image increases less than one frequency resolution element then the system is temporally coherent. Resolution in the frequency plane is controlled by the source image size at low spatial frequencies and by the spread in wavelength at high spatial frequencies. In the systems shown in Figure 1, resolution in the frequency plane depends upon the quality of L_4 or L_1 and L_2 while resolution in the image plane depends only upon the quality of L_5 or L_2 and L_3. The question thus becomes what is the effect of resolution in the frequency plane on resolution in the image plane?

First we consider the effect of temporal coherence on the image. The image intensity is the sum of the image intensities formed at each of the wavelengths present in the illuminating light. The most important effect of a spread in wavelength is on L_5. By restricting the range of wavelengths to a small fraction the design of L_5 is simplified, because chromatic aberrations are eliminated.

Next we consider spatial coherence. Lens design does not depend upon the degree of spatial coherence. The degree of spatial coherence is easily varied by varing the size of an iris diaphragm at the source for a thermal source. Temporal coherence cannot be varied nearly as easily. If the object electric field transmission of the negative contains no frequencies greater than K_o, the cutoff frequency of the transform plane is K_c and the image of the source in the transform plane extends to K_s then for an unapodized transform plane, when $K_o < K_c - K_s$ the imagery is perfectly spatially coherent and when $K_o < K_s - K_c$ the imagery is completely spatially incoherent. Two things are apparent, first a point source is not needed for coherent imagery and second merely using a source whose image just fills the transform plane does not in itself produce complete complete incoherence.

Next consider the effect of reflections on imagery. If the degree of temporal coherence is high, reflections between two glass surfaces will appear as a system of fringes instead of merely as a uniform background. The fraction of light reflected from a lens surface onto the image does not depend upon the degree of temporal coherence but the manner in which this light is distributed does. If two surfaces are separated by an optical distance of ℓ and the average wavelength of the light is λ with a spread $\Delta\lambda$, then if $\ell < (2\lambda^2 / \Delta\lambda)$, there will be fringes if the source is a thermal source. If the source is a laser, then there may be fringes at greater distances because the laser's spectrum contains complex structure within the width $\Delta\lambda$. The degree of temporal coherence should be low enough to minimize the possibility of reflection fringes and high enough to simplify lens design. If a laser is used as a source it is necessary to use the best anti-reflection coating possible on all surfaces.

So many combinations of reflections are possible that they are difficult to characterize. Some of the worst offenders are illustrated in Figure 2. The spatial frequency, K_f, of the fringes depends upon the angle between the two beams, θ, $K_f = 1/\lambda \sin\theta$. Troublesome reflection will most likely be of two types. Interference between the image and a reflected wave or interference between two different reflected waves. These fringes will be most noticeable in the darker region of the image. The intensity of fringes can be increased considerably if the small fraction of light reflected from one lens surface is focused onto a small region in the image. Such focused reflections or "ghost images" may remain a problem even with good anti-reflection coatings. For this reason, it would be a good idea to compute the reflections in an optical system before it is manufactured. N surfaces are capable of producing $1/2\, N\,(N-1)$ doubly reflected waves. Fringes produced by reflected light with a high degree of temporal coherence may be reduced or eliminated by using a lower degree of spatial coherence because bright fringes from one part of the source may coincide with the dark fringes from another part of the source.

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Now consider the effects on imagery of small defects such as scratches, digs, dust, oil droplets, and bubbles. The nature of the image caused by such a small lens defect depends upon its distance from the transform plane, (Figure 3). The small defect may be viewed in general as an out of focus point image or Fresnel Zone Plate. It is the nature of a coherent system that an image that is out of focus does not appear as a blur but as an elaborate Fresnel Diffraction pattern (Figure 4). The closer a defect is to the transform plane, the larger and fainter will be its image. A small defect near the transform plane will affect the whole image at a single frequency and be almost undetectable unless it is at a very low frequency (an on axis defect). Thus the system of Figure 1b is preferred to that of 1a because all of its glass elements and hence any defects are closer to the transform plane than the configuration of Figure 1a. In addition, if a lower degree of spatial coherence is used, the effects of the defects will be reduced further. With coherent light, the rays from an object point to an image point always pass through the same region of the lens. This is not true for incoherent light.

The statement is often made that coherent systems are sensitive to phase in the negative plane while incoherent systems are not. A photographic negative will have phase variation due to thickness variation in the base material and due to the exposed image. Thickness variation in the base causes a reduction in resolution in the frequency plane which is not important. Phase variation associated with the image will produce a slight degree of asymmetry in the modulus of the transform that is also not important to the image. The gradual phase fluctuations in the negative base do not appear in the image because their frequencies lie below the coherent cutoff frequency of any practical system. However, for a high degree of temporal coherence interference fringes may result from reflection between the front and rear surfaces of the negative that cannot be made to vanish with a reduction in spatial coherence. They may be reduced by placing the negative in the center of a sandwich of antireflection coated glass and liquid that matches the refractive index of the film. Because the front surface of this sandwich is close to the negative, it must be extremely free of small defects such as dust or liquid droplets.

It is always desired to test an optical system once it has been built. In principle, the wave phase front, coherent and incoherent transfer function and their corresponding spread functions are all related. For a coherent system it is not easy to convert all of these quantities into the coherent transfer function. An object consisting of a low contrast edge or step can provide a single method of measuring the coherent transfer function in a completed optical system [redacted] has a computer program designed to give the incoherent transfer functions from edge gradients that would give the coherent transfer function in the form: STAT

$$T_a(k) = \cos \theta_e(k)\ e^{j\,\theta_o\,(k)}$$

where $\theta_e(k)$ and $\theta_o(k)$ are the even and odd part of the phase aberrations of the coherent transfer function (JLK-106). An edge with light intensity transmissions of 100% and 70% should be of low enough contrast to give the transfer function to an accuracy of about 10%. A lowered degree of spatial coherence could be used if the source image in the transform plane is small compared to the rate of phase error fluctuations and at the expense of some error at high spatial frequencies.

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A very important point concerns the use of periodic targets as lens tests. A coherently illuminated periodic target fills only a small part of the transform plane and the complete lens system is therefore not actually tested. The same target incoherently illuminated would fill the whole transform plane and thus provide a test of the whole lens. Recently the Research Branch tested a coherent imaging system that gave a poor image of a single ten micron slit but a virtually perfect image of five five micron slits on ten micron centers. The single ten micron slit image was a good overall test of the system because the whole transform plane was filled. The five slits, although smaller in size, provided a poor test because they illuminated only three narrow regions in the transform plane. In general, any periodic target with a frequency between the transform plane cutoff frequency and one half that frequency can always be imaged perfectly with respect to contrast and resolution by a slight shift in focus. A second defect of periodic targets is that the image is virtually the same for many different planes of focus. Thus non-periodic targets such as a point or perhaps an edge are to be prefered if a single imaging test is desired.

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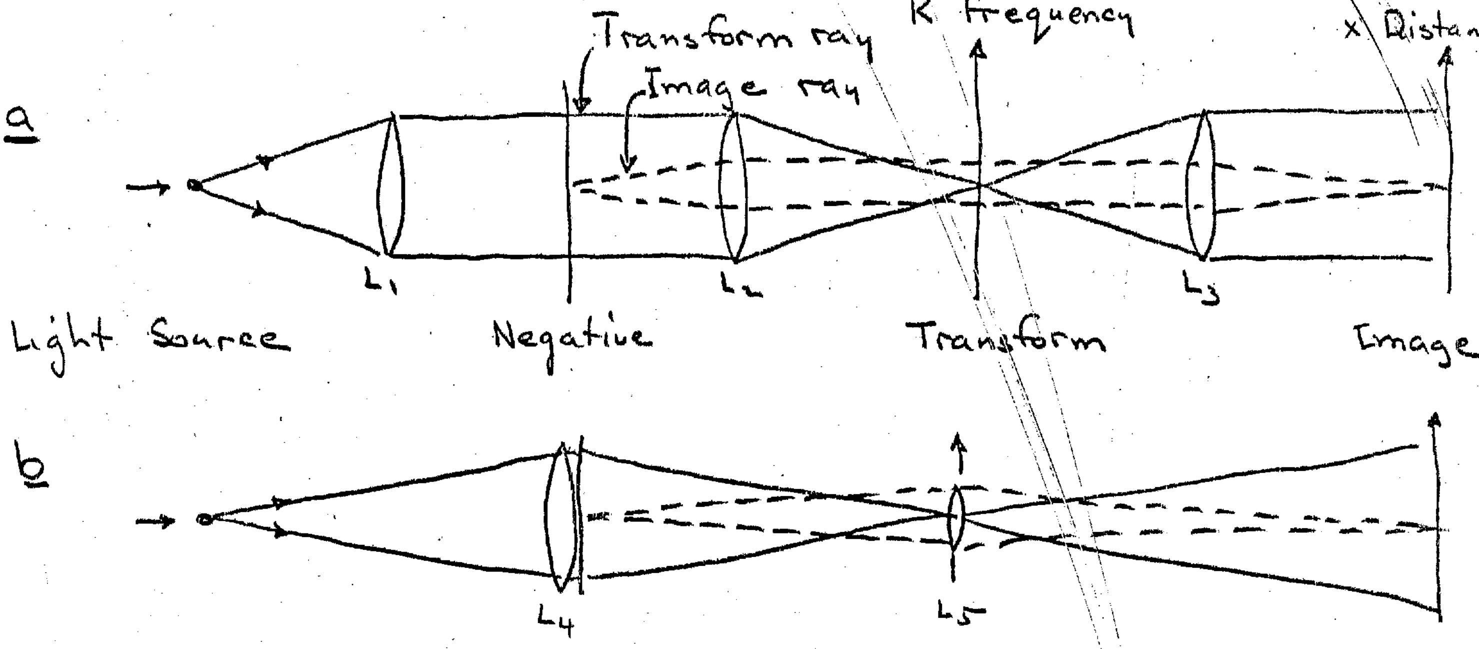
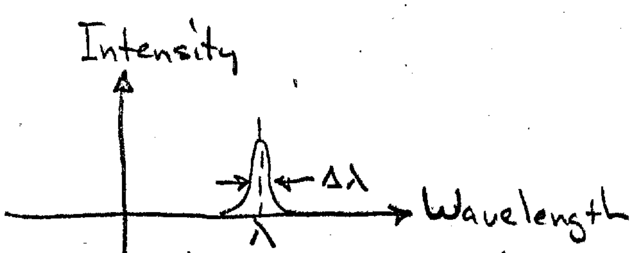
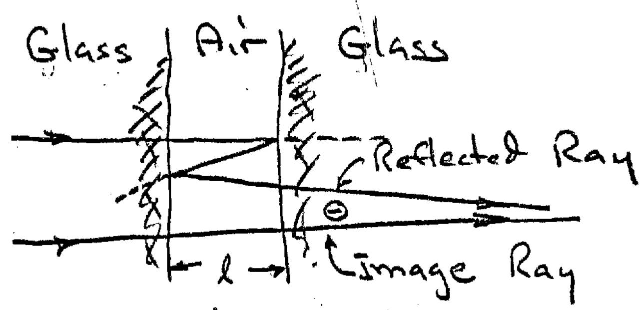


Figure 1: Two Coherent Imaging Systems

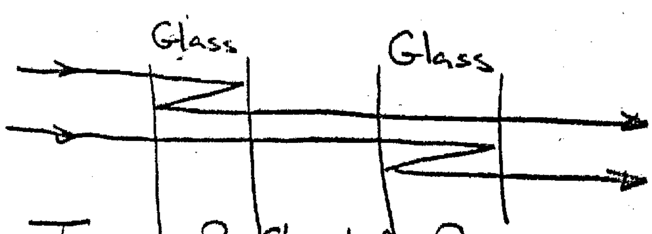


Thermal Source Spectrum

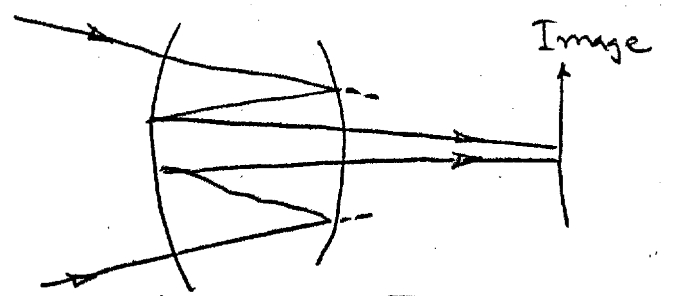


Reflected Rays Give Fringes For $l < \frac{2\lambda^2}{\Delta\lambda}$

Fringe spatial Frequency $K_f = \frac{1}{\lambda}\sin\theta$



Two Reflected Rays



Strong Intensity Fringes From Focused Reflection

Figure 2: Reflections

Figure 3 An image showing Fresnel diffraction due to a thread 10 cm. from the negative and several oil droplets closer to the negative. These droplets would not be visible if they were closer to the transform plane and off axis or if the spatial coherence was reduced.

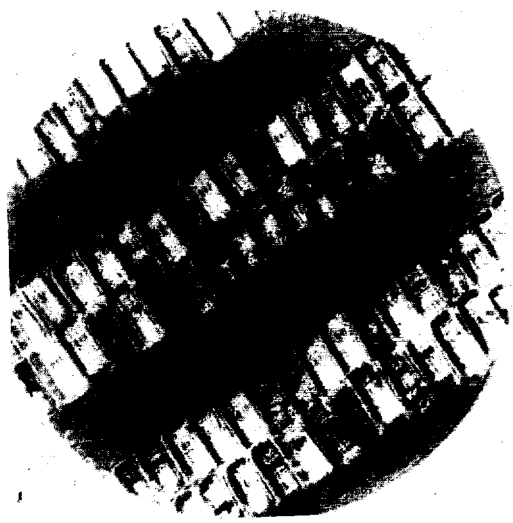


Figure 4 An image showing complex Fresnel diffraction from a negative 4 cm. out of focus. Note the high contrast of the fringes due to the periodic nature of the parked cars.